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LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

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I. INTRODUCTION

Abs

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Fahd and Steffes (1992a), under Grant NAGW-533, have shown that the opacity from gaseous SO_2 under simulated Venus conditions can be well described by the Van Vleck-Weisskopf lineshape at wavelengths shortward of 2 cm, but that the opacity of wavelengths greater than 2 cm is best described by a different lineshape that was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary

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atmospheres.

II. LABORATORY MEASUREMENTS

A. Venus

An important source of information regarding the Venus atmosphere is the increasing number of high spatial resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater et al., 1991a). Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1991), with newly conducted Magellan radio occultation experiments (Steffes et al., 1992b), and with our longer wavelength emission measurements (Steffes et al., 1990), will provide new ways for characterizing temporal and spatial variations in the abundance of both gaseous H_2SO_4 and SO_2, and for modeling their roles in the subcloud atmosphere. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous and liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981), no measurements have been made at shorter wavelengths. As a result, we conducted laboratory measurements of the 13 cm, 1.35 cm, and 3.2 mm opacity of gaseous SO_2. These measurements and their applications have been described in a paper by Fahd and Steffes (1992a); which appeared in the June 1992 issue of Icarus. (Reprints were forwarded to NASA in July 1992.) The final experiment needed for proper interpretation of the Venus millimeter-wavelength continuum was laboratory measurement of the opacity of gaseous H_2SO_4. We recently completed such measurements, and have developed a formalism for computing the millimeter-wave opacity of gaseous H_2SO_4. We have applied this formalism to our millimeter-wavelength radiative transfer model for Venus, and have found that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the lower Venus atmosphere. This work was presented at the International Colloquium on Venus (Pasadena, CA, August 10-12, Fahd and Steffes, 1992b), and is attached as Appendix A.

B. Outer Planets

Because of the large abundance of ammonia in Jupiter's atmosphere, it has not been possible to detect either the microwave or millimeter-wavelength opacities from the gaseous H_2S thought to exist deep in that atmosphere. (See, for example, Joiner et al., 1992) However, ammonia is substantially depleted in the atmospheres of Uranus and Neptune, and it has been suggested by de Pater et al. (1991b) that the pressure broadened absorption from H_2S significantly affects the centimeter wavelength emission from those planets. In order to accurately infer the abundance and distribution of H_2S in the deep atmospheres of Uranus and Neptune, either from their centimeter radio emission or from radio occultation measurements, accurate laboratory measurements of the microwave opacity from gaseous H_2S under simulated conditions for the outer planets must be conducted at centimeter wavelengths. Such a laboratory measurement program has recently been initiated at Georgia Tech, in which measurements of the opacity of gaseous H_2S in a H_2/He atmosphere are conducted at pressures from 1 to 6 Bars, at temperatures from 173 to 294K, and at frequencies of 2.25, 8.5, and 21.7 GHz. While (to date) measurements have only been conducted at room temperature, our results already indicate that the centimeter wavelength opacity from gaseous H_2S

in an H_2/He atmosphere significantly exceeds that which would be predicted using the Van Vleck-Weisskopf formalism, even when the newly measured value for H_2S line broadening (Joiner et al., 1992) is used. These preliminary results were reported in a paper presented at the Fourth International Conference on Laboratory Research for Planetary Atmospheres (October 1992, Munich) which is attached as Appendix B (Steffes et al., 1992a).

III. RADIO OCCULTATION STUDIES OF THE VENUS ATMOSPHERE WITH THE MAGELLAN SPACECRAFT

We have also been successful in this grant year in conducting a radio occultation experiment with the Magellan Spacecraft. This was the first atmospheric work conducted with Magellan and the atmosphere was probed to deeper levels than was possible with the less powerful Pioneer-Venus Orbiter radio transmission system. This experiment was conducted on October 5, 1991, and consisted of three entry occultation experiments. This successful demonstration has shown the feasibility of using the Magellan spacecraft to provide highly accurate atmospheric refractivity and absorptivity profiles, which in turn, can be used to determine profiles of temperature, pressure, and gaseous H_2SO_4 abundance in the Venus atmosphere. The preliminary results from this experiment were presented at the 1992 Meeting of the Division for Planetary Sciences of the American Astronomical Society (DPS/AAS) in Munich, Germany (October 12-17, 1992). A copy of this presentation is attached as Appendix C (Steffes et al., 1992b). In the future, we intend to use Magellan radio occultation data as part of an integrated multi-spectral analysis of Venus atmospheric data.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

In the second half of this grant year (May 1, 1992 - October 31, 1992), we published two papers. The first was published in IEEE Transactions on Microwave Theory and Techniques (special issue commemorating the International Space Year) and is entitled "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths" by Joiner, Steffes, and Noll (June, 1992). It describes our observations of Jupiter at 1.4 mm and the accompanying laboratory measurements of H_2S at that wavelengths. The second paper was published in Icarus in June and is entitled "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO_2) under Simulated Conditions for the Venus Atmosphere," by Fahd and Steffes (1992a). Reprints of both papers have been forwarded to NASA Headquarters, and distributed to interested researchers at JPL, NASA centers, and universities.

In August, we attended the International Colloquium on Venus held in Pasadena, California, and presented two papers. The first was entitled "Understanding the Variation in the Millimeter-Wave Emission of Venus" (Fahd and Steffes, 1992b) and is attached as Appendix A. The second was entitled "Long-Term Variations in the Abundance and Distribution of Sulfuric Acid Vapor in the Venus Atmosphere Inferred from Pioneer Venus and Magellan Radio Occultation Studies" by Jenkins and Steffes (1992) which presented recent results from Magellan and Pioneer-Venus radio occultation studies. In conjunction with this conference, a press conference was held on August 11 at which we described the successful radio occultation experiment conducted with Magellan. Antoine Fahd's paper reported work conducted as part of this doctoral dissertation, which was completed in May.

Copies of the dissertation were forwarded to NASA as Technical Report 1992-1.

In October we attended the 24th meeting of the Division for Planetary Sciences of the American Astronomical Society (DPS/AAS) and the accompanying Fourth International Conference on Laboratory Research for Planetary Atmospheres. Both papers presented (Steffes et al. 1992a and 1992b) are attached as Appendices B and C.

V. CONCLUSION

In the next grant year, we will continue our laboratory measurements of the centimeter wavelength opacity of gaseous H_2S under simulated conditions for the outer planets. Measurements at temperatures as low as 173K will be conducted. When all of the data is obtained, a new formalism for computing the microwave absorption from H_2S under conditions for the outer planets will be developed. This formalism will then be integrated into our radiative transfer model for the outer planets so as to study the effects of H_2S on their centimeter wavelength emission. Similarly, we will continue to obtain microwave absorptivity profiles for the Venus atmosphere from Magellan radio occultation experiments, and use them to develop profiles of H_2SO_4 vapor abundance.

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VII. APPENDICES

Presented at the International Colloquium on Venus, August 10, 1992

UNDERSTANDING THE VARIATION IN THE MILLIMETER-WAVE EMISSION OF VENUS; Antoine K. Fahd and Paul G. Steffes, School of Electrical Engineering, Georgia Institute of Technology, Atlanta, Ga. 30332.

Recent observations of the millimeter-wave emission from Venus at 112 GHz (2.6mm) have shown significant variations in the continuum flux emission [1] which may be attributed to the variability in the abundances of absorbing constituents in the Venus atmosphere. Such constituents include gaseous H_2SO_4, SO_2, and liquid sulfuric acid (cloud condensates). Recently, Fahd and Steffes [2,3] have shown that the effects of liquid H_2SO_4 and gaseous SO_2 cannot completely account for this measured variability in the millimeter-wave emission of Venus. Thus, it is necessary to study the effect of gaseous H_2SO_4 on the millimeter-wave emission of Venus. This requires knowledge of the MMW opacity of gaseous H_2SO_4 which unfortunately has never been determined for Venus like conditions.

We have measured the opacity of gaseous H_2SO_4 in a CO_2 atmosphere at 550, 570 and 590 K, at 1 and 2 atm total pressure, and at frequency of 94.1 GHz. Our results, in addition to previous centimeter-wavelength results [4] are used to verify a modeling formalism for calculating the expected opacity of this gaseous mixture at other frequencies. This formalism is incorporated into a radiative transfer model to study the effect of gaseous H_2SO_4 on the millimeter wavelength (MMW) emission of Venus.

Experimental Configuration:

The experimental setup used to measure the MMW opacity of gaseous H_2SO_4 in CO_2 atmosphere consists of a free space transmission system as shown in Figure 1. In this system, a glass cell contains the H_2SO_4/CO_2 gaseous mixture which is introduced prior to the measurement process. The glass cell is located inside a temperature-controlled chamber. A transmitting antenna is used to launch energy into the glass chamber. A receiving antenna is placed at the output of the glass cell in order to collect the outgoing signal. Using a precision variable attenuator, the resulting opacity of the gaseous mixture is measured.

Measurement Results:

The measured absorptivity (dB/km) of H_2SO_4/CO_2 at 94.1 GHz is shown in Figure 2 where it is plotted as a function of temperature for 2 and 1 atm. The reported absorptivities in Figure 2 are normalized to their respective mixing ratios. The measurements were performed at 550, 570, and 590 K in order to allow enough H_2SO_4 vapor pressure in the glass cell.

Although the measurements were performed at 94.1 GHz, care must be taken when projecting the absorption of H_2SO_4 at frequencies far from 94.1 GHz. As a result, we have developed an absorption model based on a Van Vleck-Weisskopf (VVW) formalism. In this formalism, we added the contributions from 2359 resonant lines of sulfuric acid computed by Pickett et al. (private communication, 1991) which cover frequencies between 1.5 and 450 GHz.

In order to fully implement the VVW formalism, an appropriate broadening parameter must be determined. To solve this problem, we adjusted the broadening parameter so that the calculated opacity matches the measured absorptivity at 94.1 GHz and the microwave opacities at 2.24 and 8.42 GHz reported by Steffes [4]. Comparisons between the calculated and measured opacity of H_2SO_4/CO_2 are shown in Figures 2,3, and 4. A careful examination of these results indicates that the calculated opacities of H_2SO_4 using the VVW formalism with a broadening parameter of 1.55 MHz/Torr agree well with the measured microwave and millimeter-wave opacities of the gaseous mixture. This finding is quite important since it demonstrates for the first time that the VVW formalism can be used to accurately predict the opacity of H_2SO_4/CO_2 gaseous mixture over a wide frequency range.

Modeling of the Atmosphere of Venus:

A radiative transfer model has been developed in order to investigate the effects of the atmospheric constituents of Venus on its MMW emission. Such constituents include gaseous SO_2, liquid sulfuric acid (cloud condensates), and gaseous H_2SO_4.

a) Sensitivity to Liquid H_2SO_4:

Results from the radiative transfer model indicate that liquid H_2SO_4 does indeed affect the brightness temperature of Venus at millimeter wavelengths [3]. For instance, at 112 GHz a decrease in brightness temperature of 2 K is obtained for a uniform cloud layer between 48-50 km where droplets sizes of 25 micron and a bulk density of 50 mg/m^3 are assumed. However, this decrease in brightness temperature is much less than the reported variation in the emission of Venus which indicates that variations in the abundance of liquid H_2SO_4 are not the major source of the observed brightness temperature variation.

b) Sensitivity to SO_2:

The effects of gaseous SO_2 on the computed MMW emission of Venus are well described in Fahd & Steffes [2]. Using an abundance profile of 62 ppm below an altitude of 48 km, we have found that the brightness temperature is decreased by approximately 5 K. Although this decrease is significant, it cannot completely account for the measured variation in emission.

c) Sensitivity to Gaseous H_2SO_4:

Using the developed model for the absorption of gaseous H_2SO_4 in a CO_2 atmosphere, we have found that this gaseous mixture seem to have the biggest effect on the calculated brightness temperature of Venus. Specifically at 112 GHz, a drop of 14 K is observed assuming an $H_2SO_4(g)$ abundance of 25 ppm between 48 and 38 km. This decrease in brightness temperature is quite significant compared with the effects of gaseous SO_2 and liquid H_2SO_4. Thus, we can state that the variations observed by de Pater et al. [1] are most likely due to the variations in the abundance of gaseous sulfuric acid and not to liquid sulfuric acid or gaseous sulfur dioxide as previously suggested.

A plot of the calculated millimeter-wave spectrum of Venus based on the presence of one or more constituents is shown in Figure 5. The results reported in this figure show the effect that H_2SO_4 (g) has on the MMW spectrum of Venus. In addition, the results show that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the lower atmosphere of Venus.

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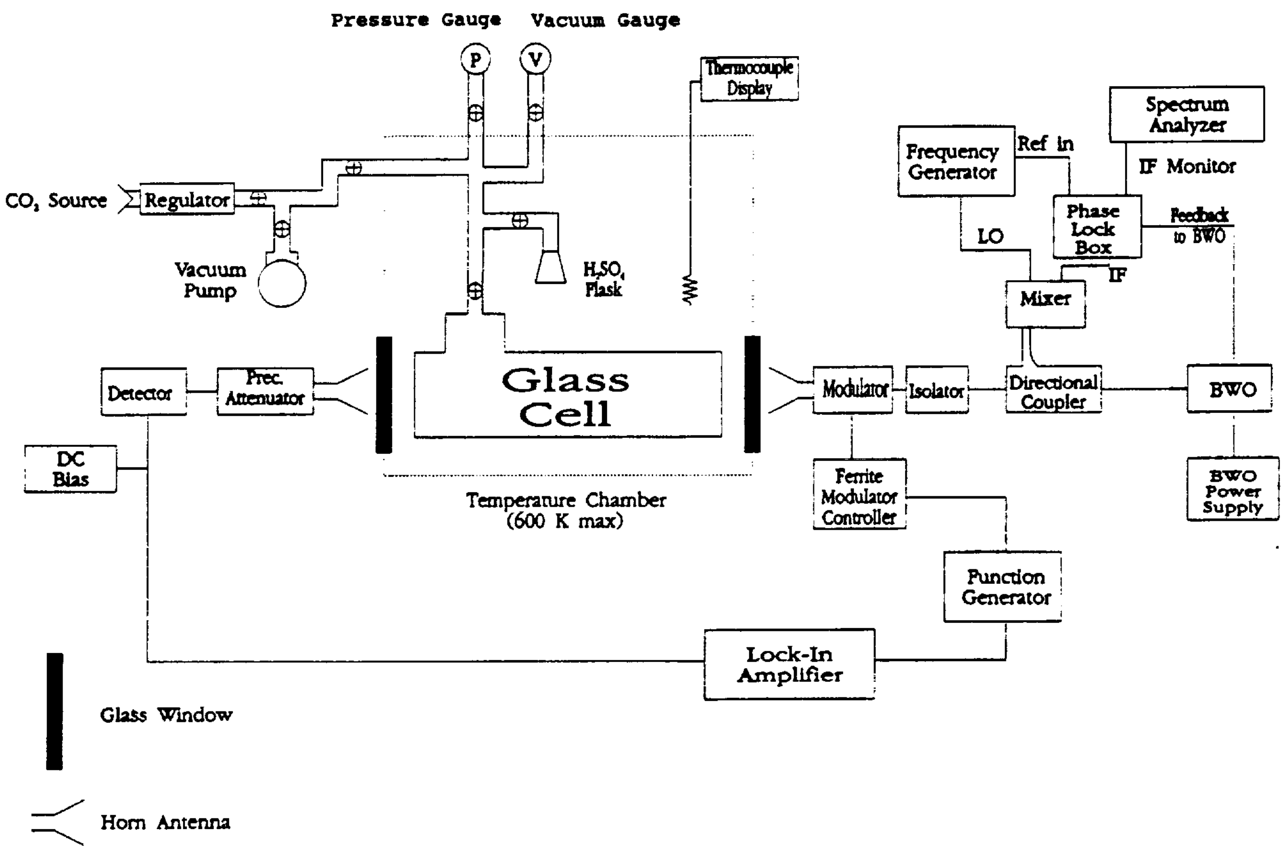

Figure 1 Block diagram of the atmospheric simulator as configured for measurements of the millimeter-wave absorption at 94.1 GHz.

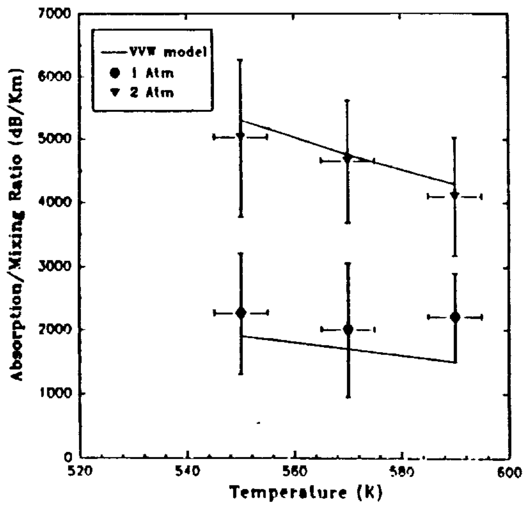

Figure 2 Laboratory measurements of the normalized absorptivity (dB/km) of gaseous H_2SO_4 in a CO_2 atmosphere at 94.1 GHz. Solid curves are the theoretically calculated absorption from the VVW formalism.

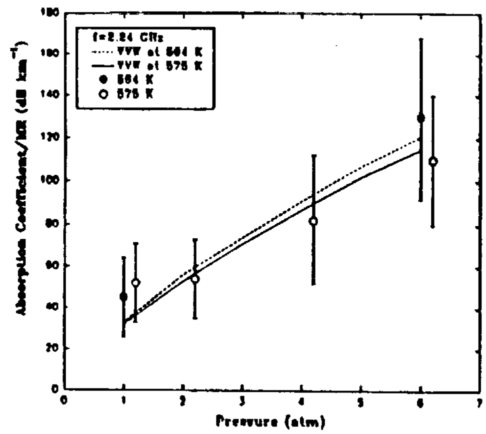

Figure 3 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985) and the calculated absorption from the VVW formalism at 2.24 GHz.

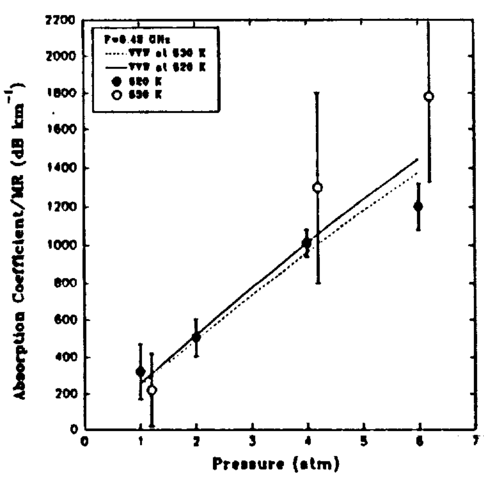

Figure 4 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985) and the calculated absorption from the VVW formalism at 8.42 GHz.

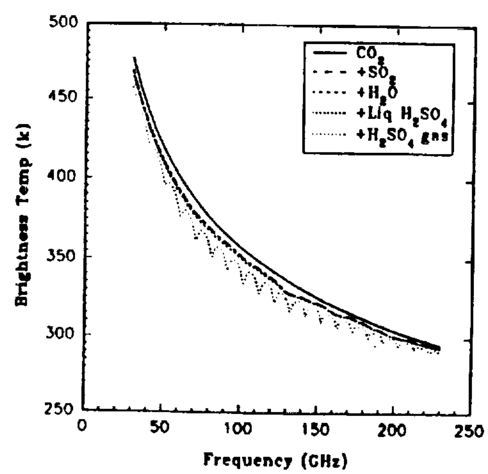

Figure 5 Comparison of the effects of atmospheric constituents on the brightness temperature of Venus between 30 and 230 GHz.

PRELIMINARY RESULTS FROM LABORATORY MEASUREMENTS OF THE CENTIMETER WAVELENGTH OPACITY OF HYDROGEN SULFIDE (H_2S) UNDER SIMULATED CONDITIONS FOR THE OUTER PLANETS

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Because of the large abundance of ammonia in Jupiter's atmosphere, it has not been possible to detect either the microwave or millimeter-wavelength opacities from the gaseous H_2S thought to exist deep in that atmosphere. (See, for example, Joiner et al., 1992, IEEE Trans. on Microwave Theory and Technique 40, June 1992; pp 1101-1109.) However ammonia is substantially depleted in the atmospheres of Uranus and Neptune, and it has been suggested by de Pater et al. (Icarus 91, June 1991, pp 220-233) that the pressure broadened absorption from H_2S significantly affects the centimeter wavelength emission from those planets. In order to accurately infer the abundance and distribution of H_2S in the deep atmospheres of Uranus and Neptune, either from their centimeter radio emission or from radio occultation measurements, accurate laboratory measurements of the microwave opacity from gaseous H_2S under simulated conditions for the outer planets must be conducted at centimeter wavelengths. Such a laboratory measurement program has recently been initiated at Georgia Tech, in which measurements of the opacity of gaseous H_2S in a H_2/He atmosphere are conducted at pressures from 1 to 6 Bars, at temperatures from 173 to 294K, and at frequencies of 2.25, 8.5, and 21.7 GHz. While (to date) measurements have only been conducted at room temperature, our results already indicate that the centimeter wavelength opacity from gaseous H_2S in an H_2/He atmosphere significantly exceeds that which would be predicted using the Van Vleck-Weisskopf formalism, even when the newly measured value for H_2S line broadening (Joiner et al., 1992, Ibid.) is used. Thus alternative lineshape models will be developed to reflect the laboratory results.

** Presented at the Fourth International Conference on Laboratory Research for Planetary Atmospheres, October 10, 1992.

I. EXPERIMENTAL APPROACH

The experimental configuration used to measure the microwave opacity of hydrogen sulfide is the same used by Steffes and Jenkins (1987) for characterizing the absorption of gaseous ammonia (NH_3) under simulated Jovian conditions. The absorptivity is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of two cavity resonators operating from 2.2 to 21.9 GHz. For this experiment a custom H_2S gas mixture was used. The pre-mixed gas mixture (obtained from Matheson) consisted of 82.71% hydrogen, 9.74% helium, and 7.35% hydrogen sulfide. (This mixing ratio was re-verified by the manufacturer immediately after the test was completed. The uncertainty is two percent of the stated component mixing ratio.) The microwave measurements made were at room temperature, but future measurements will be made at Jovian temperatures.

The planetary atmospheric simulator (shown in Figure 1) consists of a stainless steel pressure vessel in which the two cavity resonators are placed. The pressure vessel is connected via stainless steel tubing and valves to a oil diffusion vacuum pump, the tank containing the hydrogen sulfide gas mixture, and separate tanks of helium and hydrogen. The procedure for adding the gas and making microwave measurements is as follows. The valves to the gas tanks are closed and the oil diffusion pump is turned on. The pressure inside the vessel is monitored via a thermocouple vacuum gauge that is able to measure pressures between 0 and 800 Torr. When the pressure inside the vessel has reached 3 Torr or less, the pump intake valve is closed and the pump is turned off. At this point the vessel is essentially at a vacuum and measurements of the Q are taken. Additional measurements of the Q are made when a mixture of only hydrogen and helium are present. Finally, the Q is measured with the test mixture.

Included in the microwave subsystem are two cavity resonators. The large cavity resonator is operated from 2.2 to 2.3 GHz and from 8.4 to 8.7 GHz. The large cavity resonator is coupled via RG-142B coaxial cable in separate sections. The first section is located inside the pressure vessel. The RG-142B connects from the cavity itself (two ports, one for exciting the cavity and one for extracting the signal) to female-to-female type N hermetically sealed connectors (two) which feed through the pressure vessel's top stainless steel flange. UG-88/U BNC connnectors are used with the coaxial cable. The second section is outside of the pressure vessel. RG-142B is connected from the female type N connectors (two) on the outside of the flange to a microwave source and to a high resolution spectrum analyzer. The small cavity resonator is operated from 21.4 to 21.9 GHz. The small resonator has the same configuration as the large resonator except that semi-rigid cables with SMA connectors are used and female-to- female SMA hermetically sealed connectors feed through the top flange.

The microwave oscillators used were the HP 8690 A & B sweep oscillators. A 10 db attenuator is connected at the output of each oscillator to reduce the effect of variations in the coupling to the cavity resonator. These changes in coupling, which we refer to as dielectric loading, are due to the dielectric constant or permittivity of the gas mixtures and are not related to the absorptivity of the gases. The cable from the output port of the cavity resonator is connected to a high resolution spectrum analyzer. The high resolution spectrum analyzer used was the HP 8562B.

The cavity resonator operates as a bandpass filter. As a result there will be many resonances observed with the spectrum analyzer. The Q of the resonator, which is defined as the ratio of the resonant center frequency to the resonance half-power bandwidth, is proportional to the ratio of energy stored in the resonator to the energy lost per cycle. Minimal coupling is used so as to maximize Q and minimize the variations in Q that might result from changes in coupling that could occur when gases are introduced into the resonator. The resonances selected for measurement were at 2.25, 8.52, and 21.7 GHz. (Frequencies apply when the system is at atmospheric pressure and room temperature.) These resonances were chosen on the basis of their sharpness and symmetry.

The following measurements were made at each resonance: the center frequency, the signal level of the center frequency (S- resonator), the half power bandwidth, the signal level of the source (S-source is obtained by connecting the signal and excited port cables at the outside flange connectors directly together thereby by-passing the signal path through the resonator), and estimating the effect of noise on each measurement. Ten data points were obtained for each measurement above. Note that when any gas is added to or removed from the pressure vessel, the 8.5 GHz resonance is tracked on the spectrum analyzer. The frequency shift in the resonance is due the dielectric properties of the gas loading the system. Therefore it is important to always add gas slowly so as to track this shift in frequency. The reason for tracking the 8.5 GHz line is due to the close proximity of other resonances which may cause confusion in identifying the original resonance.

With the system at a vacuum, the measurements were taken and the mean computed for the data. The resulting values are given in Table One. At this point helium was added to bring the pressure to 9 psi and hydrogen was added to bring the total pressure to 76 psig (6 atmospheres). This mixture was used to evaluate the effect of dielectric loading on the system. The measurements were collected and the mean computed for the data. The results are given in Table Two. The hydrogen - helium gas mixture was then vented from the pressure vessel.

The diffusion pump was started and left on until the pressure inside the vessel was reduced to below 3 Torr.

The hydrogen - hydrogen sulfide - helium gas mixture was next added to bring the total pressure inside the vessel to 76 psig (6 atmospheres). The measurements were collected and the mean computed for the data. The results are given in Table Three. The gas mixture was then vented to reduce the pressure to 3 atmospheres. At this pressure, no opacity was detected. Finally, the pressure vessel was again evacuated. The measurments were collected and compared to the vacuum measurements obtained in Table One. This was done in order to ensure that variations hadn't occurred in the system from the time of the first measurements.

II. EXPERIMENTAL RESULTS

The following results represent the mean values of ten sampled data points collected for each measured quantity at the given gas mixture pressure.

TABLE ONE

Vacuum (3 Torr)

Frequency (GHz)	Bandwidth (KHz)	S-resonator (dBm)	S-source (dBm)
2.255	28.791	-83.121	-54.621
8.531	78.13	-73.223	-44.182
21.717	1262.9	-40.85	-29.007

Table Two

6 Atmospheres(76 psi) of H_2-He

Frequency (GHz)	Bandwidth (KHz)	S-resonator (dBm)	S-source (dBm)
2.253	30.900	-83.529	-54.403

8.525	78.250	-76.503	-43.585
21.701	1183.3	-42.04	-28.680

Table Three

6 Atmospheres(76 psi) of H_2-He-H_2S

Frequency (GHz)	Bandwidth (KHz)	S-resonator (dBm)	S-source (dBm)
2.251	32.775	-80.842	-55.134
8.518	85.990	-71.583	-44.584
21.683	1182.7	-42.901	-29.062

For a relatively low-loss gas mixtures, the relation between the absorptivity of the gas mixture and its effects on the Q of a resonance is given by:

$$\alpha = 8.686\,(Q_L^{-1} - Q_C^{-1})\,\pi/\lambda \tag{1}$$

where α is the absorptivity of the gas mixture in dB/km, Q_L is the quality factor of the cavity resonator when the gas mixture is present, Q_C is the quality factor of the cavity resonator in a vacuum, and λ is the wavelength in km. However, to account for dielectric loading one can use the equation:

$$\alpha = 8.686\,(Q_L^{-1} - Q_{g'}^{-1})\,\pi/\lambda \tag{2}$$

where Q_L is the quality factor of the lossy gas mixture, $Q_{g'}$ is the quality factor of the same density mixture <u>without</u> the lossy gas, α is the absorptivity of the gas mixture in dB/km, and λ is the wavelength in km. Using this equation and the data in Tables Two and Three the absorptivites are:

$f = 2.25$ GHz $\alpha = .173$ dB/km

$f = 8.52$ GHz $\alpha = .710$ dB/km

$f = 21.7$ GHz $\alpha =$ not detectable

These results are plotted in Figure 2 , along with the expected opacity from this gas mixture computed using the Van Vleck-Weisskopf formalism. (See Joiner et al., 1992.)

III. EXPERIMENTAL UNCERTAINTIES

Experimental uncertainties in the measurement of the absorptivity coefficients of the gaseous mixture can be divided into two major categories: uncertainties due to noise and instrumental uncertainties. In the case of instrumental uncertainties, most of the uncertainties stem from the accuracy of the equipment that measures the bandwidth of the resonance (δf). Additional instrumental uncertainties include the measurement accuracy of f_0 and of t. For the cases of bandwidth, center frequency, and transmissivity measurement, an accuracy of 5% was achieved and is included in the error bars in Figure 2 and Table Four.

Additional instrumental uncertainties result from asymmetry of the resonances, uncertainties in the measured total pressure, temperature uncertainties, and uncertainties in the mixing ratio. In the case of resonance asymmetry (resonance asymmetry results from the interference of neighboring resonances with the desired resonance), we have found that the absorption coefficients at 2.24 GHz are not greatly affected by the asymmetry effect. In contrast, the asymmetry analysis seems to affect some of the results at 21.7 GHz and the resulting additional uncertainties have been added to the error bars.

In the case of pressure measurement, the accuracy was limited by the equality of the pressure gauge used in the experiment which had a 0.2 atm accuracy throughout its usable range. The mixing ratio uncertainty is two percent of the stated component mixing ratio.

The uncertainties from noise in the system are primarily due to the large insertion loss of the cavities used in the system (required to keep the quality factor high). To account for noise uncertainties, repeated measurements were conducted at each particular pressure. As a result, statistics were developed to account for the variations of Q, t, and δf which were subsequently used to develop 1-σ error bars for the absorption coefficient of the H_2S gas mixture.

CONCLUSION

The results obtained from this experiment show that in a 6 atm hydrogen/helium atmosphere, hydrogen sulfide is more opaque at centimeter wavelengths than predicted by Van-Vleck Weisskopf theory. The noted variation from Van Vleck-Weisskopf theory parallels variations from that theory for both NH_3 (Joiner and Steffes, 1991) and for SO_2 (Fahd and Steffes, 1992) in that it is more pronounced at the wavelengths farthest from the line centers, i.e., at lower frequencies. Further measurements are needed with hydrogen sulfide in order to explain the discrepancies. Likewise, work with H_2S at colder temperatures is needed to characterize its effect on the centimeter wavelength emission spectra of Uranus and Neptune.

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Joiner, J. and P.G. Steffes (1991). Modeling of Jupiter's millimeter wave emission utilizing laboratory measurements of ammonia (NH_3) opacity. Journal of Geophysical Research 96, 17,463-17,470.

Joiner, J., P.G. Steffes, and K.S. Noll (1992). Search for sulfur (HS) on Jupiter at millimeter wavelengths. IEEE Trans. on Microwave Theory and Technique 40, 1101-1109.

Steffes, P.G. and J.M. Jenkins (1987). Laboratory measurements of the microwave opacity of gaseous ammonia (NH_3) under simulated conditions for the Jovian atmosphere. Icarus 72, 35-47.

TABLE FOUR

ABSORPTIVITY OF H_2S AT THREE MICROWAVE FREQUENCIES

Frequency (GHz)	Measured Absorption α (dB/km)	Measurement Error (dB/km) $\pm 1\sigma_\alpha$	VVW Prediction (dB/km)
2.25	0.171	±0.047	0.01
8.50	0.704	±0.164	0.14
21.7	< 4.00	----	0.90

NOTE: Pressure = 6.1 atmospheres Temperature = 22C +/- 2C
Mixture = 82.71% H_2, 9.74% He, 7.55% H_2S

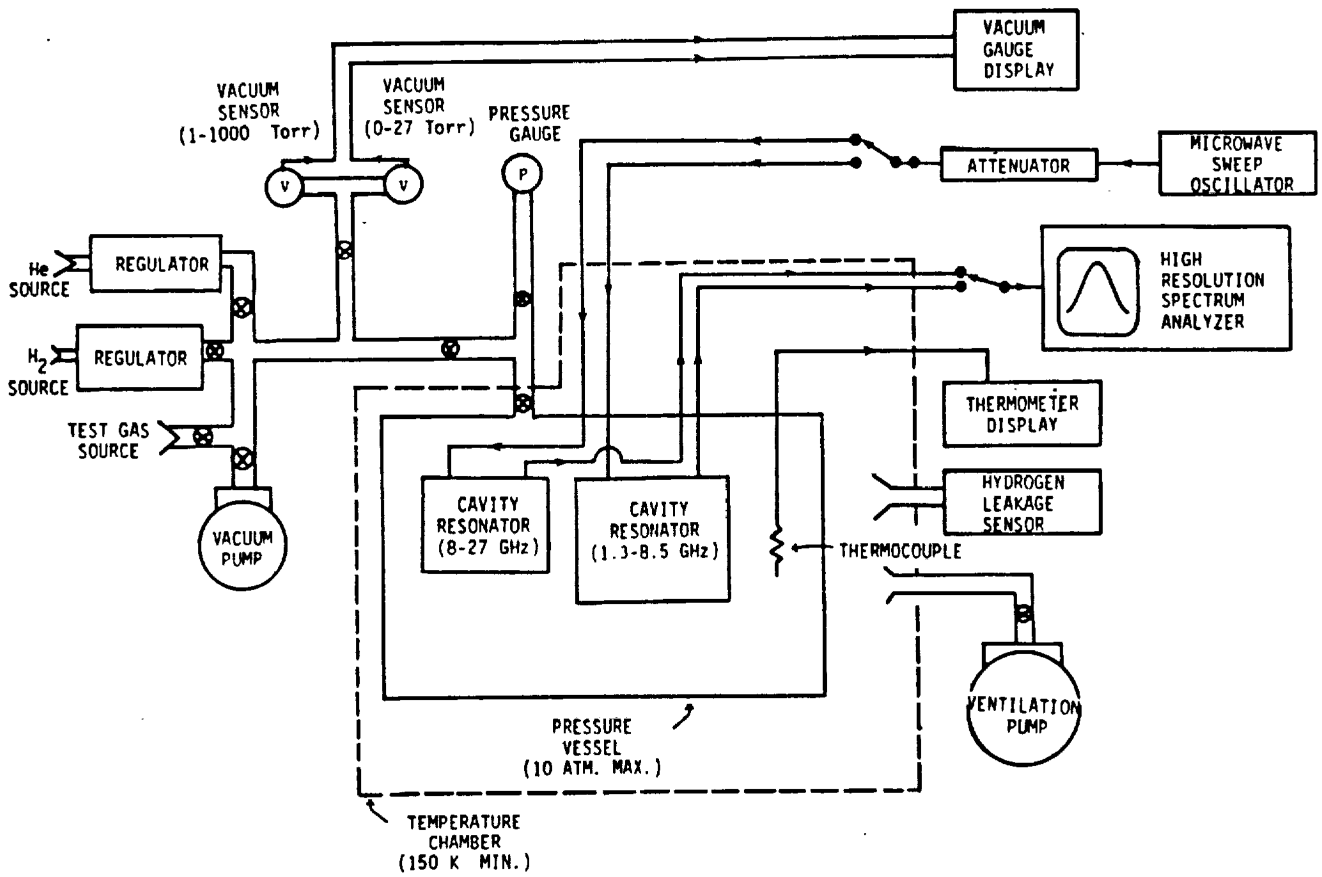
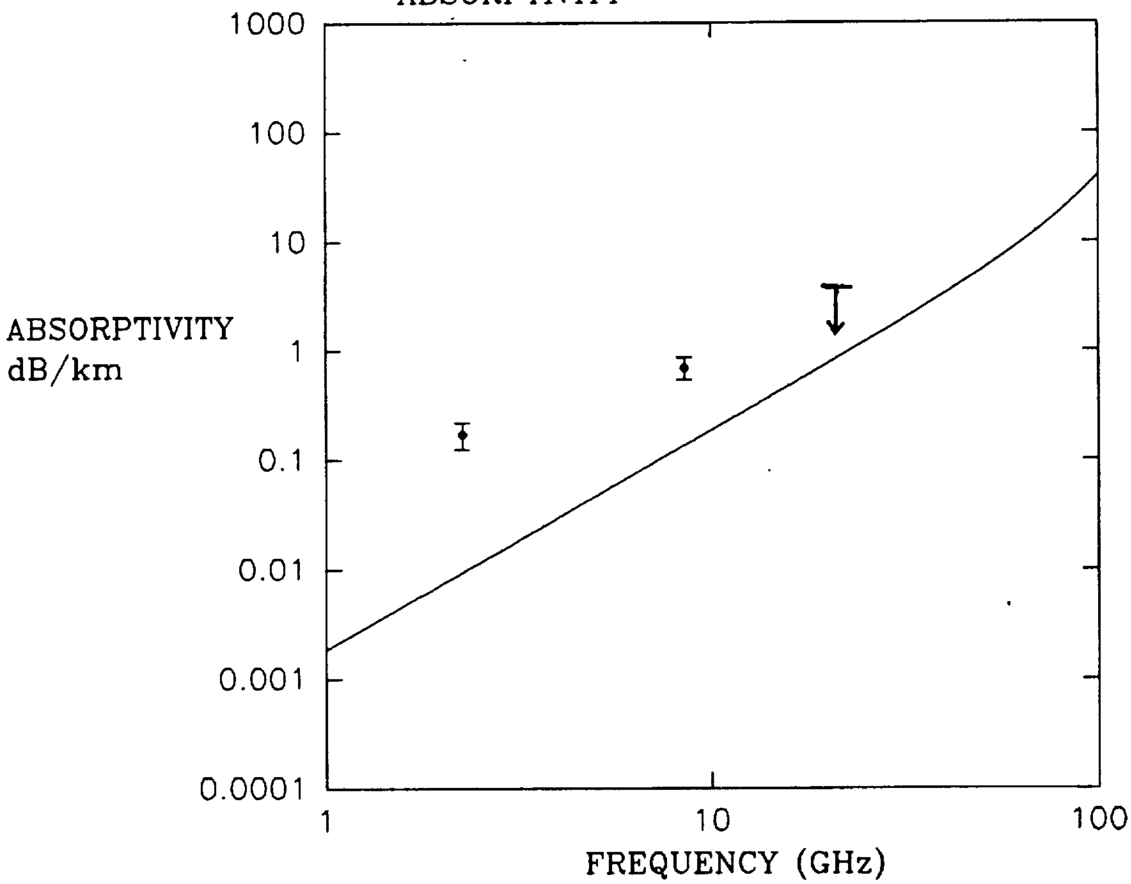


Figure 1: Block diagram of atmospheric simulator as configured for measurement of the microwave opacity from H_2S under simulated outer planets conditions

FIGURE 2:

COMPARISON OF EXPERIMENTAL VERSUS VVW PREDICTION FOR HYDROGEN SULFIDE ABSORPTIVITY



PRESSURE = 6.1 ATM TEMPERATURE = 295K
MIXTURE = 82.71% HYDROGEN
9.74% HELIUM
7.55% HYDROGEN SULFIDE

APPENDIX C:

DIVISION FOR PLANETARY SCIENCES ABSTRACT FORM

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Preliminary Results from the October 1991 Magellan Radio Occultation Experiment

P.G. Steffes (Georgia Inst. of Technology), J.M. Jenkins (SETI Institute/NASA-Ames R.C.), G.L. Tyler, J. Twicken (Stanford Univ.), R.S. Austin, and S.W. Asmar (JPL/CalTech)

On October 5 and 6, 1991, dual-frequency radio occultation measurements of the polar Venus atmosphere were conducted on three successive orbits using the telecommunications system aboard the Magellan spacecraft and the 70 meter DSN antenna at Tidbinbilla, Australia. The high radiated power (EIRP) from the spacecraft, plus the accurate positioning of the spacecraft antenna, has made it possible to develop highly accurate profiles of atmospheric refractivity and absorptivity down to the 36 km level at 3.6 cm, and down to the 34 km level at 13 cm. A polarimetric measurement was also conducted at the 3.6 cm wavelength in an attempt to detect any effects of clouds or lightning on the polarization of the transmitted wave.

No depolarization events have been detected, but preliminary profiles of atmospheric absorptivity provide accurate profiles of absorbing constituent abundances, especially for gaseous H_2SO_4.

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Figure 1-1

ATMOSPHERIC RADIO OCCULTATION MEASUREMENTS WITH MAGELLAN AT VENUS

5 OCTOBER 91 - 6 OCTOBER 91

GOALS: OBTAIN REFRACTIVITY AND ABSORPTIVITY PROFILES OF VENUS ATMOSPHERE TO LOWEST POSSIBLE ALTITUDES..

CONDUCT EXPERIMENT AT TWO FREQUENCIES: 2298 MHz (13 cm)
8425 MHz (3.6 cm)

SO AS TO ACHIEVE HIGHER ACCURACY....

USE ABSORPTIVITY PROFILES TO CHARACTERIZE ABUNDANCE AND DISTRIBUTION OF GASEOUS H_2SO_4 AND IDENTIFY SPATIAL AND TEMPORAL VARIATIONS OF SAME.

DEVELOP T-P PROFILES FROM REFRACTIVITY PROFILES AND CORRELATE VARIATIONS WITH VARIATIONS IN H_2SO_4 ABUNDANCE, AND WITH MAPS MADE BY GALILEO NIMS.

ADVANTAGES OVER PREVIOUS RADIO OCCULTATION EXPERIMENTS:

MUCH HIGHER EIRP (EFFECTIVE ISOTROPIC RADIATED POWER) FROM MAGELLAN RESULTS IN PROFILES WITH SMALLER ERROR BARS AND ALLOWS PROBING MUCH DEEPER INTO THE ATMOSPHERE. AS A COMPARISON WITH PREVIOUS PIONEER-VENUS RESULTS:

	PIONEER-VENUS	MAGELLAN
DEPTH PROBED AT 13 CM:	39 km	33.8 km
DEPTH PROBED AT 3.6 CM:	52 km	35.6 km
BENDING ANGLE MEASURED (MAXIMUM) AT 13 CM:	8 degrees	15.5 degrees
BENDING ANGLE MEASURED (MAXIMUM) AT 3.6 CM:	1.5 degrees	11.0 degrees

CHALLENGES:

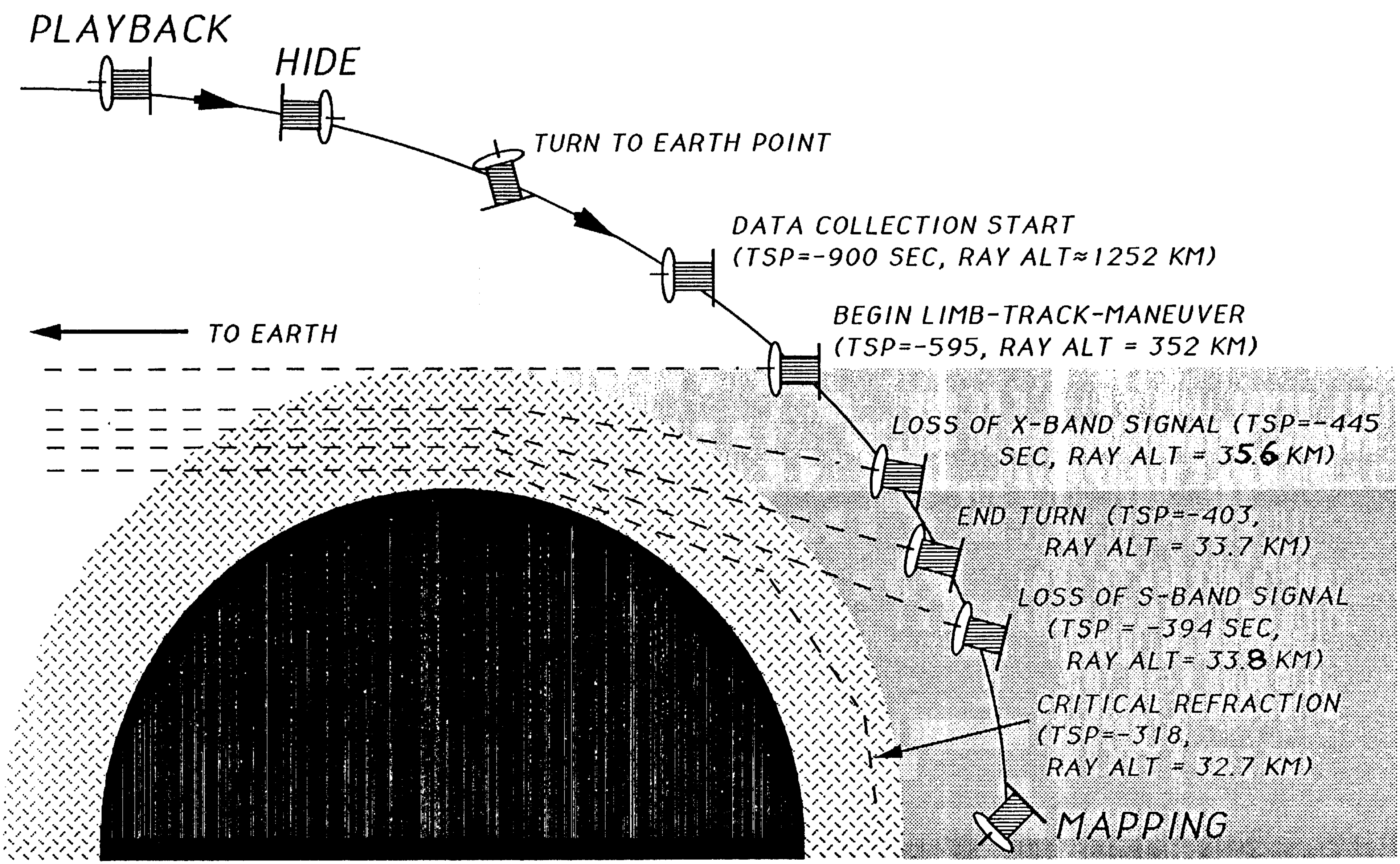
REQUIRED DEVELOPMENT OF SPECIAL SPACECRAFT TRACKING MANEUVER SO AS TO KEEP SPACECRAFT HIGH-GAIN ANTENNA POINTED TOWARD THE LIMB OF THE PLANET (AND THUS THE RAY PATH BACK TO EARTH).

SPECIAL OPERATION OF 70-METER GROUND STATION (DSS-43)

5 OCTOBER RADIOSCIENCE EXPERIMENT PROFILE

Figure-1-2

- Measure abundance of H_2SO_4 by determining atmospheric absorptivity (signal attenuation) and refractivity (signal doppler shift) during occultation.



REGION PROBED BY MAGELLAN RADIO OCCULTATION
EXPERIMENT (ORBIT #3212)

LATITUDE: 61 - 69 degrees North

LONGITUDE: 85 - 93 degrees East (Just West of the Tethus Regio)

SOLAR ZENITH ANGLE: 107-112 degrees (Night side, near terminator)

FIGURE 2

Figure 3-1: Strength of 8425 MHz signal (3.6 cm) during Occultation Experiment

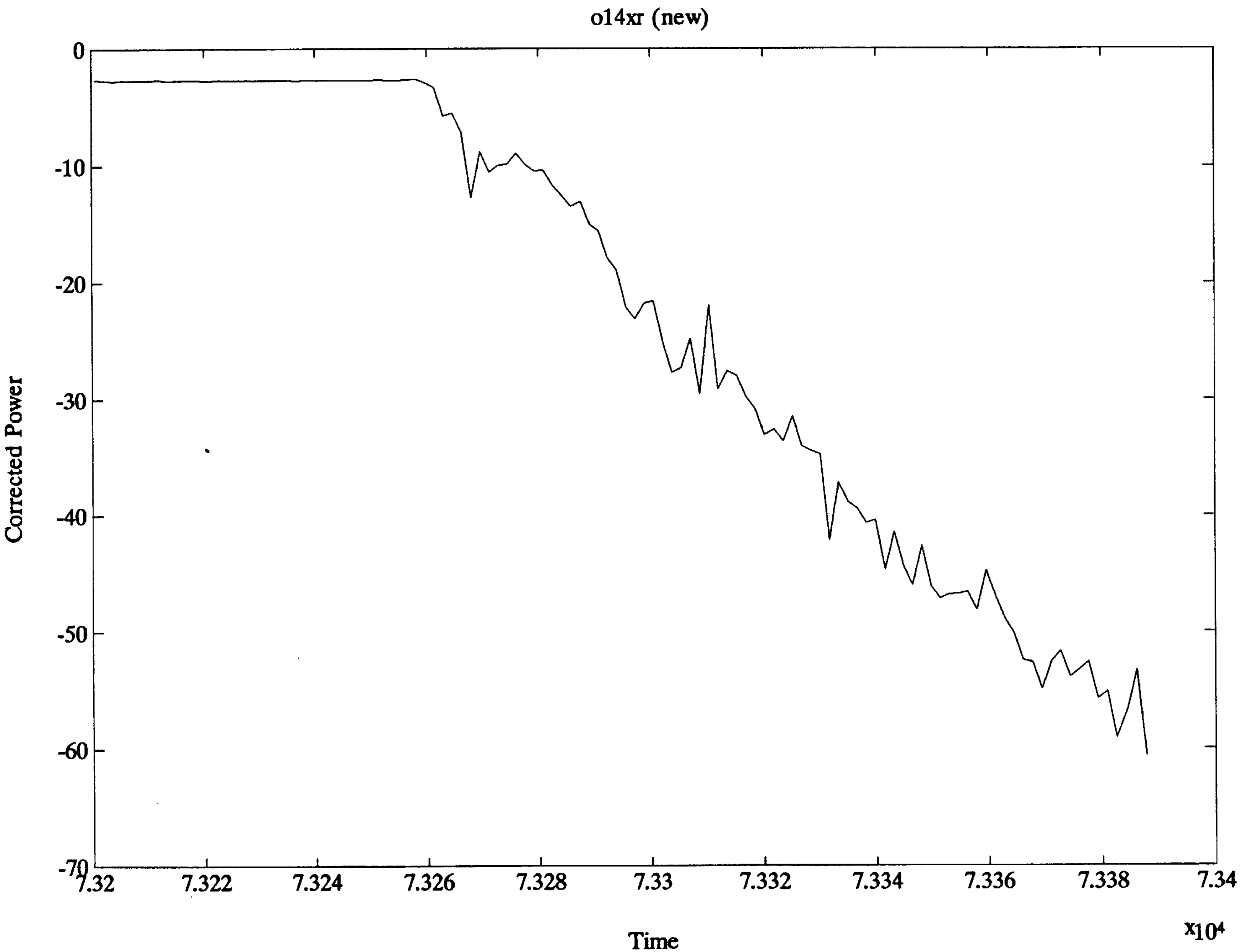


Figure 3-2: Stength of 2298 MHz signal (13 cm) during Occultation Experiment

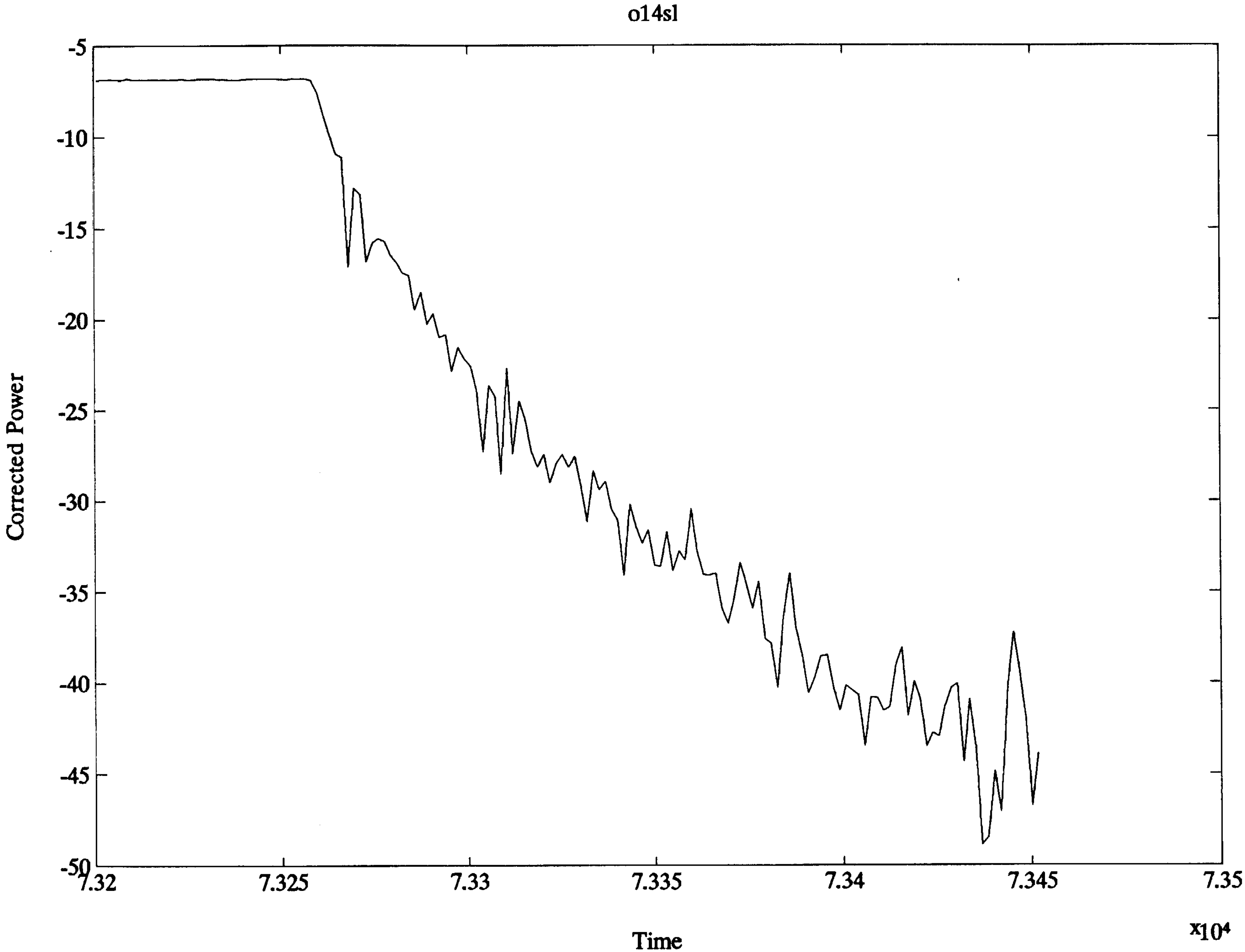


Figure 4-1: Bending of 3.6 cm signal during occultation experiment

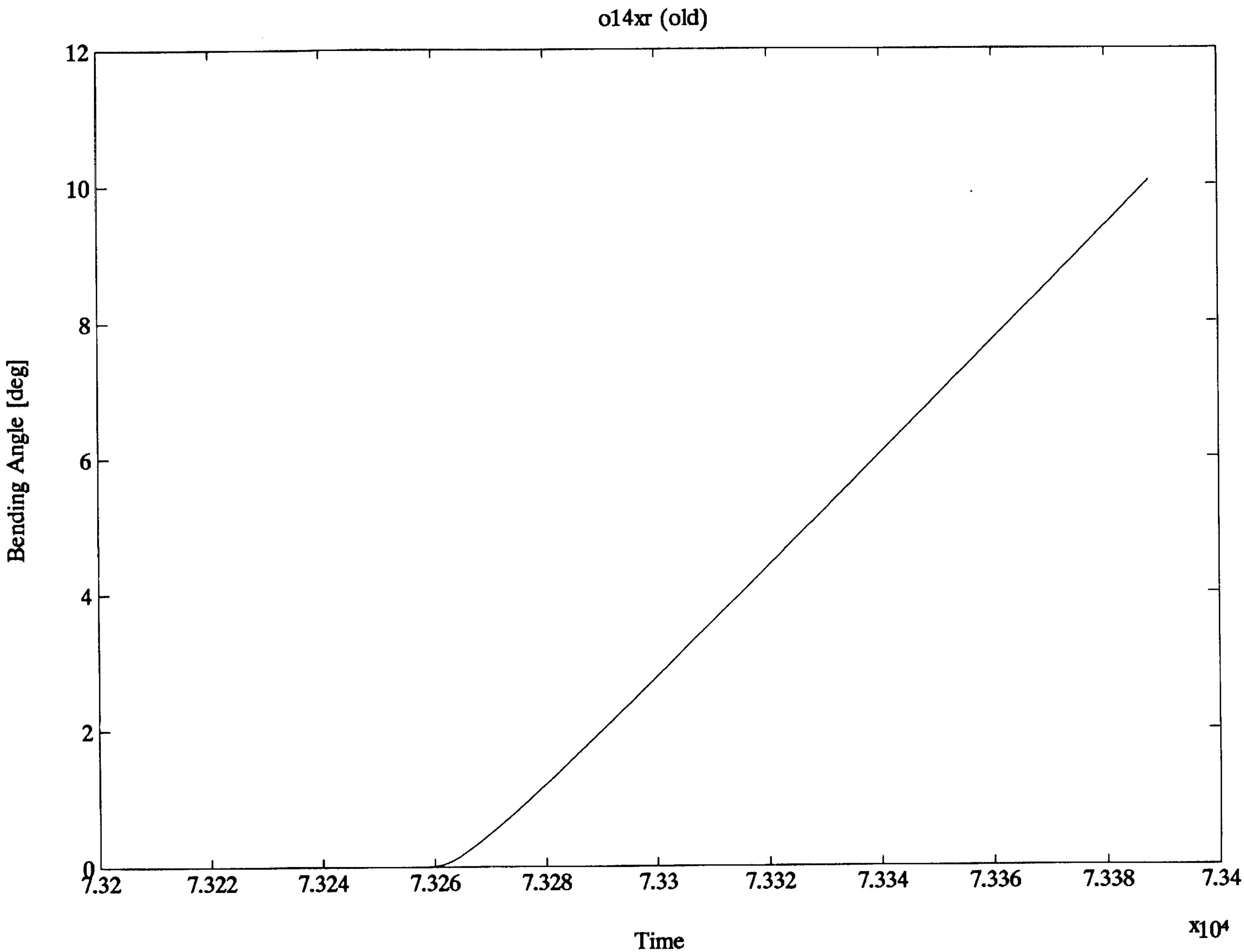


Figure 4-2: Bending of 13 cm signal during occultation experiment

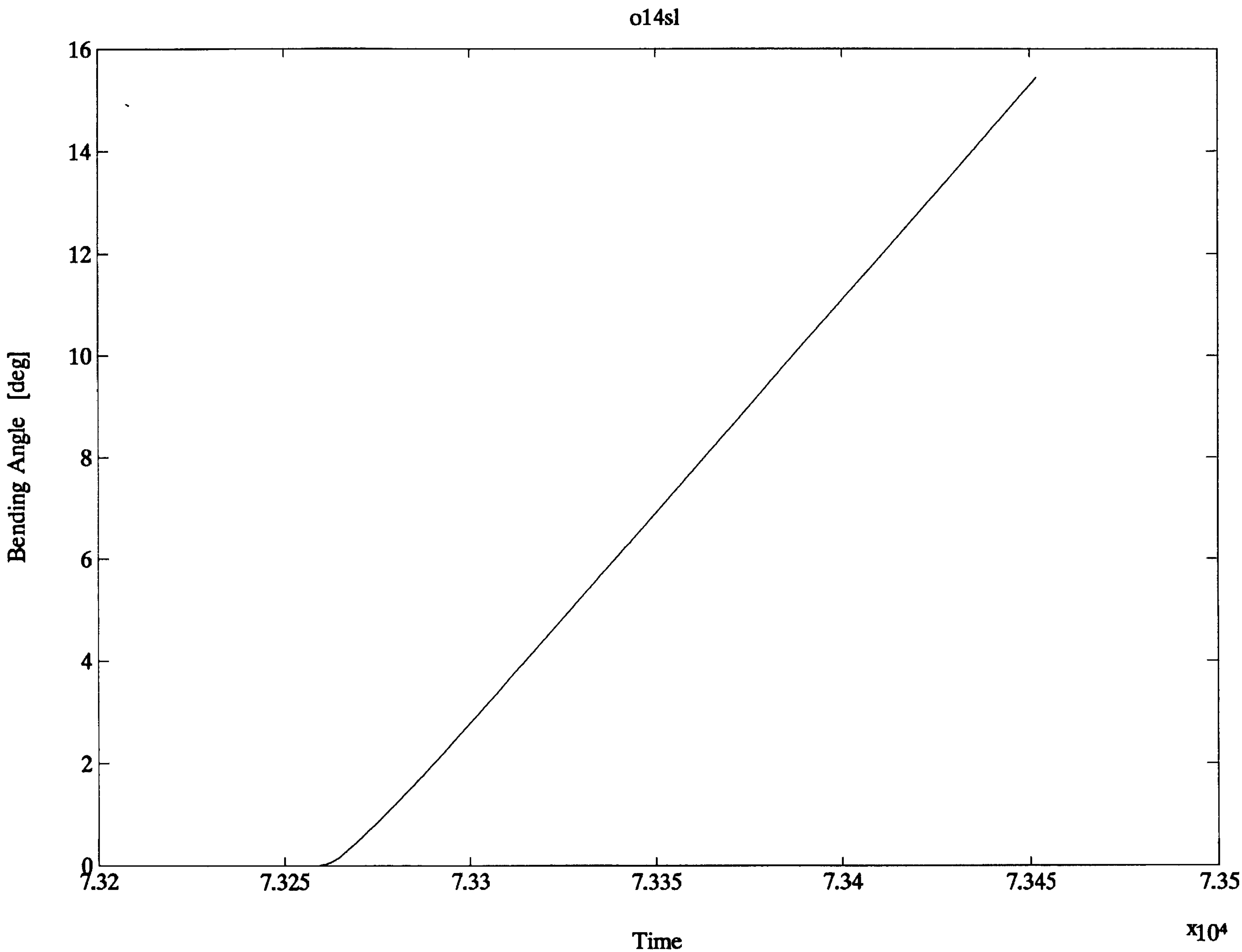
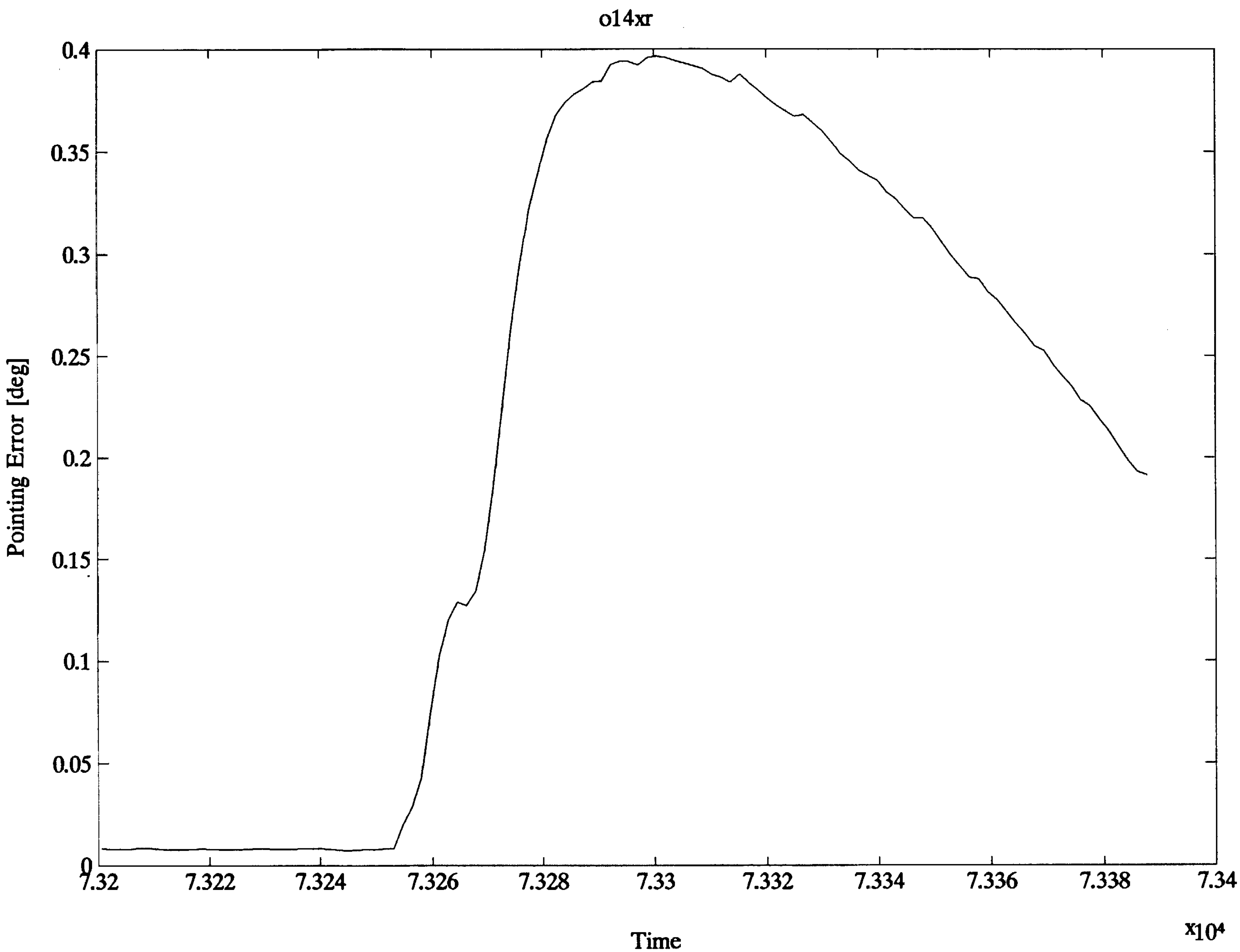


Figure 5: Accuracy of antenna pointing maneuver relative to actual ray bending



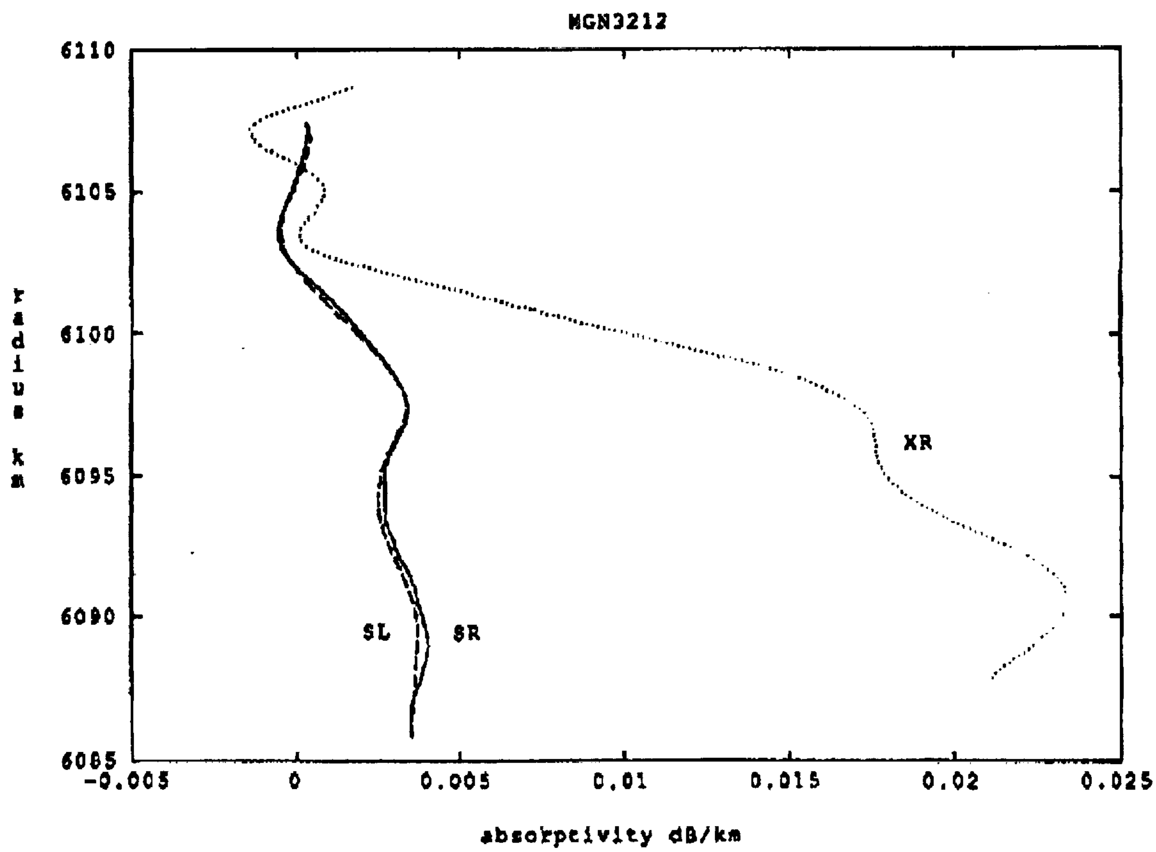

MGN3212
6110
6105
6100
6095
6090
6085
radius km
-0.005
0
0.005
0.01
0.015
0.02
0.025
absorptivity dB/km
XR
SL
SR

Figure 6-1

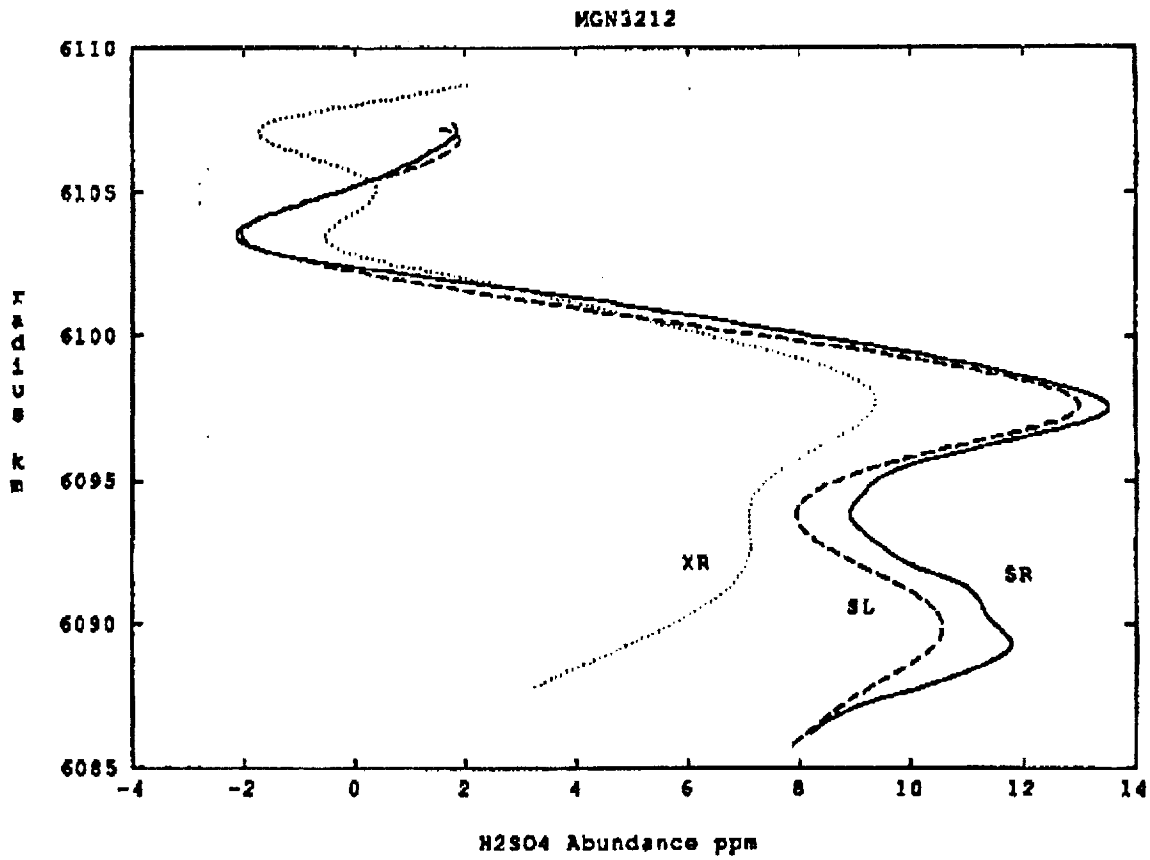

MGN3212
6110
6105
6100
6095
6090
6085
-4
-2
0
2
4
6
8
10
12
14
radius km
H2SO4 Abundance ppm
XR
SL
SR

Figure 6-2

Contributors to the Magellan Radio Occultation Experiment

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- Figure 7 -